Rev. Int. Contam. Ambie. 38 (Sustainable Architecture and Urban Environment) 81-98, 2022
https://doi.org/10.20937/RICA.54416

STUDY ON BONDING COMPRESSION-SHEAR PERFORMANCE BETWEEN INDUSTRIAL GREEN FIBER-REINFORCED CONCRETE AND OLD CONCRETE

Estudio sobre el rendimiento de la compresión-cizalla de unión entre el hormigón industrial reforzado con fibra verde y el hormigón antiguo

Yan LI[1], Rong-Hua ZHAO[1], Wen-Yang DONG[2]* and Qi-Ren JIANG[1]

[1] School of Civil Engineering, Jilin Jianzhu University, Changchun, Jilin Province, China.
[2] Computer Science and Technology Engineering Center, The 964th Hospital, Changchun, Jilin Province, China.

*Author for correspondence: delwine@126.com

(Received May 2021, accepted September 2021)

Key words: green environmental protection, industrial green fiber-reinforced concrete, old and new concrete, bonding compression-shear performance, numerical simulation

ABSTRACT

Industrial green fiber-reinforced concrete, a new hybrid high performance environmental protection material, can be made by adding recycled steel fibers into concrete in a certain proportion. As a composite material used in the construction industry, it can provide a new research direction for national green and sustainable development. This paper studied the interface bonding mechanism of normal steel fiber-reinforced old and new concrete and industrial green fiber-reinforced concrete and old concrete by using a self-made new fixture, and discussed the influence of compressive stress, types of steel fibers and recycled steel fiber content on the bonding compression-shear performance of specimens. The results show that the bonding compression-shear performance of specimens gradually increases with the increases of the compressive stress acting perpendicular to the shearing surface within the range of low compressive stress, and when the compressive stress is from 0.2 MPa to 1.0 MPa, the increased amplitude of the bonding compression-shear performance of specimens gradually increases, when the compressive stress is from 0.6 MPa to 1.0 MPa, the increased amplitude of the bonding compression-shear performance of specimens reaches the maximum, and when the compressive stress is from 1.0 MPa to 1.4 MPa, the increased amplitude of the bonding compression-shear performance of specimens decreases. Under the same conditions, the effect of the recycled steel fibers on improving the bonding compression-shear performance between old and new concrete is better than normal steel fibers. The bonding compression-shear performance between old and new concrete gradually increases with the increases of the volume ratio of recycled steel fibers, and when the fiber content is from 0.0% to 1.0%, the increased amplitude of the bonding compression-shear performance of specimens gradually increases, when the fiber content is from 0.5% to 1.0%, the increased amplitude of the bonding compression-shear performance of specimens reaches the maximum, and when the fiber content is from 1.0% to 1.5%, the increased amplitude of bonding compression-shear performance of specimens decreases. The simulation results of industrial green fiber-reinforced concrete and old concrete specimens with fiber content of 1.5% under different compressive stresses are basically in agreement with the experimental results. This study can provide references for the research of bonding compression-shear behavior of steel fiber-reinforced old and new concrete materials and the recycling of steel wire from waste tires.

Palabras clave: protección ambiental verde, concreto industrial verde reforzado con fibras, concreto viejo, concreto nuevo, compresión de unión, rendimiento de corte, simulación numérica

RESUMEN

El hormigón industrial reforzado con fibra verde, un nuevo material híbrido de alto rendimiento para la protección del ambiente, se puede fabricar añadiendo fibras de acero recicladas en el hormigón en cierta proporción. Como material compuesto utilizado en la industria de la construcción, puede proporcionar una nueva dirección de investigación para el desarrollo ecológico y sostenible nacional. Este documento estudió el mecanismo de unión de interfaz de hormigón reforzado con fibra de acero normal, hormigón viejo y nuevo, y hormigón reforzado con fibra verde industrial y hormigón viejo mediante el uso de un nuevo artefacto de fijación y discute la influencia de la tensión de compresión, tipos de fibras de acero y contenido de fibra de acero reciclado en el rendimiento de compresión-cizalla de unión de las muestras. Los resultados muestran que el rendimiento de compresión-cizallamiento de las muestras aumenta gradualmente con los aumentos de la tensión de compresión que actúa perpendicular a la superficie de cizallamiento dentro del rango de baja tensión de compresión. Cuando la tensión de compresión es de 0.2 MPa a 1.0 MPa, la amplitud incrementada del rendimiento de compresión-cizalla de unión de las muestras aumenta gradualmente. Cuando la tensión de compresión es de 0.6 MPa a 1.0 MPa, la amplitud incrementada del rendimiento de compresión-cizalla de unión de las muestras alcanza el máximo, y cuando el esfuerzo de compresión es de 1.0 MPa a 1.4 MPa, la amplitud incrementada del rendimiento de compresión-cizalla de unión de las muestras disminuye. En las mismas condiciones, el efecto de las fibras de acero recicladas en la mejora del rendimiento de la compresión-cizalla de unión entre el hormigón viejo y nuevo es mejor que las fibras de acero normales. El rendimiento de compresión-cizalla de unión entre el hormigón viejo y el nuevo aumenta gradualmente con los aumentos de la relación de volumen de las fibras de acero recicladas. Cuando el contenido de fibra es de 0.0% a 1.0%, la amplitud aumentada del rendimiento de compresión-cizalla de unión de las muestras aumenta gradualmente. Cuando el contenido de fibra es de 0.5% a 1.0%, el aumento de la amplitud del rendimiento de compresión-cizalla de unión de las muestras alcanza el máximo. Cuando el contenido de fibra es de 1.0% a 1.5%, la amplitud incrementada del rendimiento de compresión-cizalla de unión de las muestras disminuye. Los resultados de simulación de hormigón industrial reforzado con fibra verde y muestras de hormigón antiguo con un contenido de fibra del 1.5% bajo diferentes tensiones de compresión están básicamente de acuerdo con los resultados experimentales. Este estudio puede proporcionar referencias para la investigación del comportamiento de compresión-cizalla de materiales de hormigón viejos y nuevos, reforzados con fibra de acero, y el reciclaje de alambre de acero de neumáticos de desecho.

INTRODUCTION

Concrete is widely used because of its availability of local materials, low price, simple production, fire resistance and good durability. But it also has shortcomings, such as: concrete is a kind of non-homogenous material, which often produces micro-cracks in the building structure, which leads to the damage of the building materials of concrete structure with the change of time and environmental conditions. With the continuous development of concrete structures, the safety and normal operation of major structural projects has become a social problem that has a significant impact on the security of national economy. According to the past experience, the concrete structure is usually reinforced and strengthened by increasing the section method, outsourcing concrete reinforcement method, changing the force transmission way reinforcement method and other technical methods, which have been included in the "Technical Code for Reinforcement of Concrete Structures". Such as increasing the section method and outsourcing concrete reinforcement method which has been widely applied (Liu 2014, Cui 2018), and in practical engineering, when the two methods are used in the design and construction, the problem that the cooperative work of new part and the original material must be solved first, so as to ensure that the old and new concrete has a higher bonding strength, that is, both involve the bonding problem between the old and new concrete (Chen and Zheng 2005).

In recent years, in order to make the bonding surface between old and new concrete has good mechanical properties and extend the durability of the use of concrete structure, adding a certain amount of normal steel fibers and other repair materials into the new concrete during its mixing process as research work has been gradually developed (Cheng et al. 2013). As a new type of composite material, normal steel fiber-reinforced concrete can effectively improve the properties of concrete, such as compressive resistance, tensile resistance, bending resistance and shear resistance, and delay the generation and development of concrete cracks. However, there are few research on the mechanical properties of the bonding surface between old and new concrete when the recycled steel fibers formed by the steel wire from waste tires are used as a reinforced material in the new concrete. Recycled steel fibers are better than normal steel fibers in tensile strength, yield strength and other mechanical properties (Peng et al. 2015). Although its price is similar to or slightly higher than normal steel fibers, as the volume of normal steel fibers is small, the amount of normal steel fibers under the same volume ratio is much more than that of recycled steel fibers. Therefore, using recycled steel fibers in engineering is more economical and reasonable than normal steel fibers. And according to statistics, in recent years, the production of waste tires in China and the world is huge (Kang and Zhang 2011), the wire accounts for 21~30% of the total waste tire weight. Therefore, making recycled steel fibers from waste tires as reinforcement material can not only save resources and protect the environment, but also provide a new research direction for national green and sustainable development (Carrillo et al. 2020).

RESEARCH BACKGROUND

For many years, scholars at home and abroad have done a lot of research on the interface bonding performance between old and new concrete and the properties of recycled steel fiber-reinforced concrete. Chen et al. (1995) explored the influence of adding carbon fiber into new concrete on the bonding strength between old and new concrete. The results show that the bonding-shear strength between old and new concrete is greatly improved and the bond is more firm with the addition of carbon fiber. Caggiano et al. (2017) conducted compression and bending tests on industrial SFRC and recycled SFRC, and the results show that recycled steel fibers produced by waste tires could replace industrial steel fibers and play a good role in strengthening concrete. Bing et al. (2021) explored the mechanical properties and failure criteria of concrete under the combined compression-shear stress. The results show that the peak shear strength and corresponding shear displacement of concrete increase with the increases of normal stress ratio. Simalti et al. (2021) studied the compressive, split tensile, and flexural performance of ordinary self-compacting concrete, self-compacting concrete containing manufactured steel fibers and self-compacting concrete containing recycled steel fibers. The results show that when the volume ratio of steel fibers is 1.5%, the self-compacting concrete containing recycled steel fibers has better overall performance than the other two kinds of concrete, and is more economical and environmentally friendly. Many universities in China have also done a lot of experimental research on the bonding performance of the interface between old and new concrete. Cheng H.Q. (2007) conducted an experimental study on the bonding performance between steel fiber-reinforced concrete and old concrete. The results show that the addition of fibers can significantly improve the bonding-shear performance between old and new concrete, and within a certain range of fiber content, the bonding-shear strength between old and new concrete increases with the increases of fiber content. Liu (2014) made a detailed study on the failure criterion of recycled concrete under the composite compression-shear stress. Based on the analysis of the test data and the failure strength criterion of common concrete, the plane compression-shear strength criterion of recycled concrete applicable to composite stress conditions is deduced.

However, the above studies mainly focus on the bonding mechanical properties between normal old and new concrete, normal steel fiber-reinforced concrete and old concrete and the performance of recycled steel fiber-reinforced concrete, and there are few studies on the bonding compression-shear performance of the interface between recycled steel fiber-reinforced concrete (i.e. industrial green fiber-reinforced concrete) and old concrete. In general, the bonding surface between old and new concrete is often under the composite stress state of pull, pressure and shear (Yuan and Liu 2001, Zhao et al. 1999). Therefore, it is of great significance to study the bonding compression-shear performance of the bonding surface between old and new concrete under the composite stress state for the quality of construction engineering. Therefore, on the basis of the previous research for the bonding failure performance between old and new concrete, this paper adopts a new self-made fixture as the assistant to carry out the bonding compression-shear test between normal steel fiber-reinforced old and new concrete, industrial green fiber-reinforced concrete and old concrete under the composite stress state on fifty-seven standard bond cube specimens. The influence of compressive stress, types of steel fibers and content of recycled steel fibers on bonding compression-shear performance of specimens was discussed, and the expression of the bonding compression-shear strength between old and new concrete was established. The numerical simulation of bonding compression-shear performance between industrial green fiber-reinforced concrete and old concrete specimens was also carried out. This study can provide references for the research of compression-shear behavior of steel fiber-reinforced old and new concrete materials, also for the recycling of steel wire from waste tires and the green and sustainable development of building structures.

EXPERIMENTAL PROGRAMS AND RESULTS ANALYSIS

Experimental materials

The new concrete used in this test, namely industrial green fiber-reinforced concrete, has a strength grade of C40, while the old concrete, namely ordinary Portland cement concrete, has a strength grade of C30. The steel fibers selected for the new concrete are normal steel fibers and recycled steel fibers, of which the length and diameter of the normal steel fibers are 30 mm and 0.5 mm, as shown in **figure 1a**. The recycled steel fibers was made of high-strength wire from waste tires from a tire recycling and treatment company. After manual polishing, the rubber on the surface was removed. After cutting, the length was 45 mm and the diameter was 1.5 mm, as shown in **figure 1b**. According to various theories of fiber reinforcement mechanism such as fiber spacing theory and composite material theory (Nourmohammadi et al. 2020, Liu et al. 2018), fiber volume ratio is one of the main influencing factors of fiber reinforcement effect. Therefore, the volume ratio of normal steel fibers and the recycled steel fibers used in this test are 0.0%, 0.5%, 1.0% and 1.5%. The fibers are uniformly distributed in the new concrete matrix during the test (Raju et al. 2020).

Treatment of surface roughness of old concrete

It is important to deal with and evaluate some conditions of the old concrete surface such as the roughness of the specimen surface for the bonding between the new concrete and old concrete before pouring the new concrete (Diab et al. 2017, Tschegg et al. 2000). Considering the simplicity of the test operation and the representativeness of the test, artificial chiseling was used for the old concrete interface during the test. According to the treatment experience of previous researchers, the optimal roughness of the bonding interface after artificial chiseling was about 4.5 mm. Therefore, the average sand filling depth is about 4.0-4.7 mm after the artificial light chisel treatment of the old concrete surface to remove part of the cement floating slurry on the surface (A_1-type interface).

a) b)

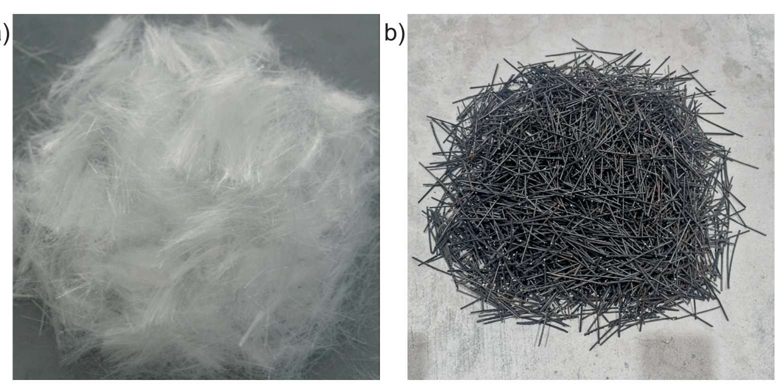

Fig. 1. Types of steel fibers, a) Normal steel fibers; b) Recycled steel fibers.

After chiseling treatment of the old concrete interface, the concrete interface binder (R_1-type interface agent) produced by a certain unit was used for brushing. Binder was brushed on the old concrete surface side, the thickness is about 1.0-1.5 mm.

Loading scheme

The experiment was carried out in the laboratory of Jilin Jianzhu University in Changchun, Jilin Province. When the 150mm×150mm×150mm composite cube specimen with half new and half old concrete is subjected to multi-axial stress, the loading direction of compressive stress is perpendicular to the bonding interface between the old and new concrete, and the shear stress is parallel to the bonding interface, that is, the shearing surface coincides with the bonding interface between the old and new concrete, as shown in **figure 2a**. In order to facilitate the stable and continuous stress of the specimen, a fixture is needed to assist the test operation. The loading situation is shown in **figure 2b**. The schematic diagram of the self-made Z-shaped steel plate is shown in **figure 3a**, the self-made new fixture is composed of iron block with holes, iron plate and bolts, its schematic diagram is shown in **figure 3b**. To reduce the friction between the compression surface of the specimen and the loading block, two sliding rollers are used to contact, and aluminum sulfide ointment is applied on the rollers to reduce the impact of friction. Use sandpaper to polish the compression surface of the specimen, ensure that the surface of the test block is smooth. Before loading, the concrete specimen is fixed in a self-made fixture, and then the Z-shaped steel plate is placed on the compression side of the concrete. After the sliding roller is placed, the test block is pressed by a vertical jack, and then the shear stress is exerted by a transverse jack. The loads are measured by the load sensor, and the displacement

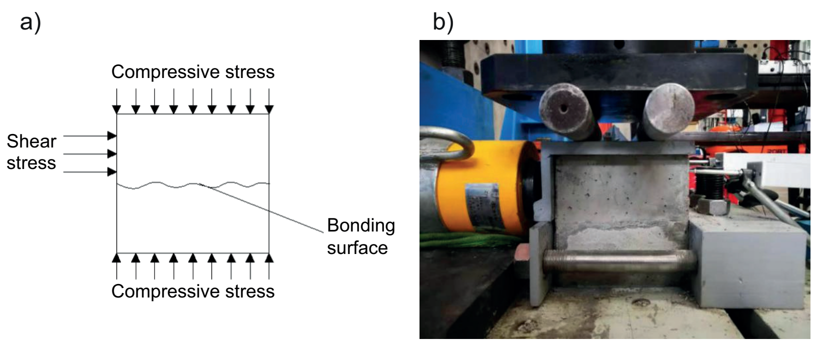

Fig. 2. The compression-shear test of the specimen, a) Schematic diagram of instrument compression-shear test; b) Diagram of test instrument and installation.

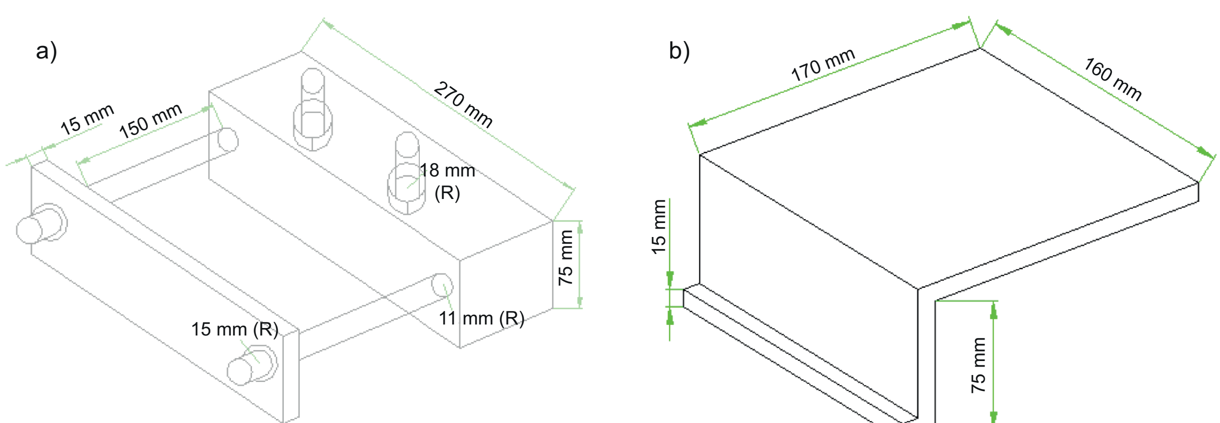

Fig. 3. Schematic diagram of self-made device for testing, a) Schematic diagram of self-made Z-shaped steel plate; b) Schematic diagram of self-made fixture device.

is input to the computer for storage and processing by the displacement meter through the acquisition board during the test.

During the test loading, the compressive stress was first loaded to a set of fixed values, and then the shear stress was applied after continuous stable state until the specimen reached failure. The compressive stress has four grades of 0.2 MPa, 0.6 MPa, 1.0 MPa and 1.4 MPa. Under each case of compressive stress, the variation range of fiber content is 0.0%-1.5%. Nineteen groups of composite cube specimens were used for the study, and three specimens were made in each group.

Test data results

The test results of the influence of different normal steel fiber contents on the shear stress of the specimen and the influence of different recycled steel fiber contents on the shear stress of the specimen under different compressive stress levels are shown in **table I** and **table II**.

Failure phenomenon of specimens

After the bonding compression-shear test, the observation of the bonding-shear surface shows that the damage of a few concrete blocks appears in the new concrete or the old concrete, while other damage mostly appears on the bonding interface between the interface agent and the old and new concrete, accompanied by the interface agent cross-section phenomenon. The bonding surfaces between old and new concrete have different degrees of loosening, but also accompanied by some debris. In addition, some of the old and new concrete test blocks under the compressive stress of 1.0 MPa and 1.4 MPa also have different degrees of damage at the bottom interface. For some specimens under the compressive stress of 1.4 MPa, the damage of the surfaces around the old concrete is obvious. The new fixture made by ourselves has few damage and has good use effect. The damage of the bonding specimen is shown in **figure 4**.

Influence of compressive stress on bonding compression-shear performance between old and new concrete

In the process of experimental analysis, τ / f_a is taken as the measurement index of bonding compression-shear strength, where τ is the peak shear stress. $f_a = (f_{c1} + f_{c2}) \times 0.67/2$, f_{c1} is the compressive strength of the old concrete cube, and f_{c2} is the compressive strength of the new concrete cube. **Figure 5** shows the variation of bonding compression-shear strength relative index τ / f_a of the cube specimens under different compression-shear stresses. It can be seen from the figure that within the range of low compressive stress of 0.2 MPa-1.4 MPa, the bonding compression-shear strength of specimens with the same content of recycled steel fibers gradually increases with the increases of compressive stress, and when the compressive stress is from 0.2 MPa to 1.0 MPa, the increased amplitude of the bonding compression-shear strength of specimens gradually increases, when the compressive stress is from 0.6 MPa to 1.0 MPa, the increased amplitude of the bonding compression-shear strength of specimens reaches the maximum, and when the compressive stress is

TABLE I. BONDING COMPRESSION-SHEAR STRENGTH BETWEEN NORMAL STEEL FIBER-REINFORCED CONCRETE AND OLD CONCRETE UNDER DIFFERENT FIBER CONTENTS.

No.	Fiber content	Binder	Bonding compression-shear strength			Number	Compressive stress / MPa
			Breaking load / kN	Fracture strength / MPa	The mean / MPa		
$S_1A_1R_1$	0.5%	Interface agent	19.36 19.67 19.29	0.860 0.874 0.857	0.864	3	0.6 MPa
$S_2A_1R_1$	1.0%	Interface agent	21.24 21.58 21.88	0.944 0.959 0.972	0.958	3	0.6 MPa
$S_3A_1R_1$	1.5%	Interface agent	23.31 23.79 24.62	1.036 1.057 1.094	1.062	3	0.6 MPa

TABLE II. BONDING COMPRESSION-SHEAR STRENGTH BETWEEN INDUSTRIAL GREEN FIBER-REINFORCED CONCRETE AND OLD CONCRETE UNDER DIFFERENT COMPRESSIVE STRESSES.

No.	Fiber content	Binder	Bonding compression-shear strength			Number	Compressive stress / MPa
			Breaking load / kN	Fracture strength / MPa	The mean / MPa		
$N_0A_1R_1$	0.0%	Interface agent	14.69 14.95 14.67	0.653 0.664 0.652	0.656	3	0.2 MPa
$S_{11}A_1R_1$	0.5%	Interface agent	15.22 15.56 15.89	0.676 0.692 0.706	0.691	3	0.2 MPa
$S_{22}A_1R_1$	1.0%	Interface agent	17.67 18.45 19.99	0.785 0.820 0.888	0.831	3	0.2 MPa
$S_{33}A_1R_1$	1.5%	Interface agent	20.22 21.28 21.83	0.899 0.946 0.970	0.938	3	0.2 MPa
$N_0A_1R_1$	0.0%	Interface agent	18.43 19.02 18.52	0.819 0.845 0.823	0.829	3	0.6 MPa
$S_{11}A_1R_1$	0.5%	Interface agent	19.53 19.91 20.72	0.868 0.885 0.921	0.891	3	0.6 MPa
$S_{22}A_1R_1$	1.0%	Interface agent	21.98 22.50 22.89	0.977 1.000 1.017	0.998	3	0.6 MPa
$S_{33}A_1R_1$	1.5%	Interface agent	22.34 24.14 26.81	0.993 1.073 1.192	1.086	3	0.6 MPa
$N_0A_1R_1$	0.0%	Interface agent	22.01 23.04 24.95	0.978 1.024 1.109	1.037	3	1.0 MPa
$S_{11}A_1R_1$	0.5%	Interface agent	23.58 24.46 25.81	1.048 1.087 1.147	1.094	3	1.0 MPa
$S_{22}A_1R_1$	1.0%	Interface agent	26.71 26.96 27.47	1.187 1.198 1.221	1.202	3	1.0 MPa
$S_{33}A_1R_1$	1.5%	Interface agent	28.55 28.76 29.16	1.269 1.278 1.296	1.281	3	1.0 MPa
$N_0A_1R_1$	0.0%	Interface agent	27.13 26.59 28.59	1.206 1.182 1.271	1.220	3	1.4 MPa
$S_{11}A_1R_1$	0.5%	Interface agent	25.42 28.21 31.36	1.130 1.254 1.394	1.259	3	1.4 MPa
$S_{22}A_1R_1$	1.0%	Interface agent	30.20 30.45 31.69	1.342 1.353 1.408	1.368	3	1.4 MPa
$S_{33}A_1R_1$	1.5%	Interface agent	32.52 32.83 33.31	1.445 1.459 1.480	1.461	3	1.4 MPa

Fig. 4. Bonding compression-shear damage of the specimen.

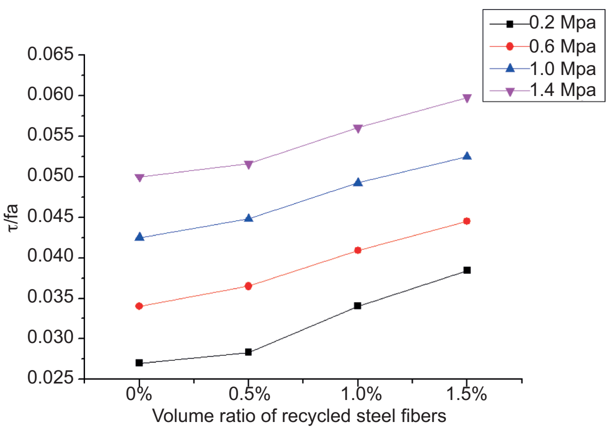

Fig. 5. Influence of compressive stress on bonding compression-shear strength of specimens.

from 1.0 MPa to 1.4 MPa, the increased amplitude of the bonding compression-shear strength of specimens decreases. In addition, it can be seen that with the increases of the content of recycled steel fibers, the bonding compression-shear strength of specimens gradually increases, and when the fiber content is from 0.0% to 1.0%, the increased amplitude of the bonding compression-shear strength of specimens gradually increases, when the fiber content is from 0.5% to 1.0%, the increased amplitude of the bonding compression-shear strength of specimens reaches the maximum, and when the fiber content is from 1.0% to 1.5%, the increased amplitude of bonding compression-shear strength of specimens decreases.

Influence of types of steel fibers on bonding compression-shear performance between old and new concrete

Figure 6 shows the influence of types of steel fibers on the bonding compression-shear strength of

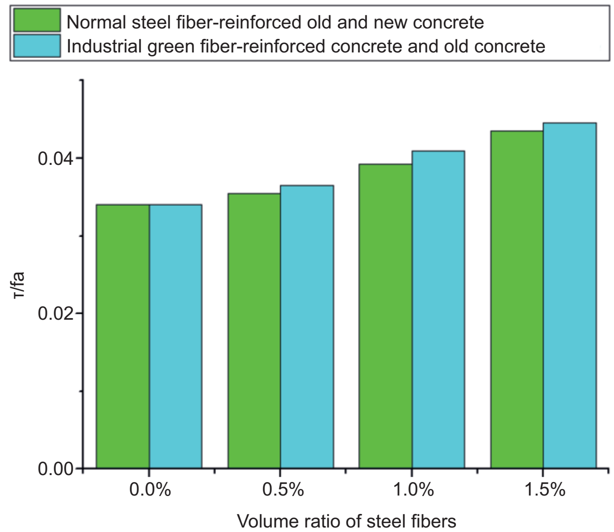

Fig. 6. Influence of types of steel fibers on bonding compression-shear strength of specimens.

steel fiber-reinforced old and new concrete when the compressive stress is 0.6 MPa. It can be calculated that when the fiber content is 0.5%, the bonding compression-shear strength indexes of normal steel fiber-reinforced old and new concrete, industrial green fiber-reinforced concrete and old concrete are 0.0354 and 0.0365, respectively. When the fiber content is 1.0%, the strength indexes are 0.0393 and 0.0409, respectively. When the fiber content is 1.5%, the strength indexes are 0.0435 and 0.0445, respectively. Therefore, within a certain range of volume ratio of steel fibers, the effect of recycled steel fibers on improving the bonding compression-shear performance between old and new concrete is better than that of normal steel fibers.

Influence of volume ratio of recycled steel fibers on bonding compression-shear performance between old and new concrete

Figure 7 is the bonding compression-shear strength index-slip relationship curves of the bonding surface with different volume ratios of recycled steel fibers under various compressive stress levels collected by the test with the help of the self-made compression-shear fixture (Liu 2000). As can be seen from the figure, when the compressive stress is the same, the relationship of the relative slip peak value is $s_{1.5\%} > s_{1.0\%} > s_{0.5\%} > s_{0\%}$. In other words, within the range of fiber content of 0.0%-1.5%, the bonding compression-shear strength of specimens increases with the increases of the volume ratio of recycled steel fibers (Li et al. 2020), which is consistent with the conclusion obtained from **figure 5**.

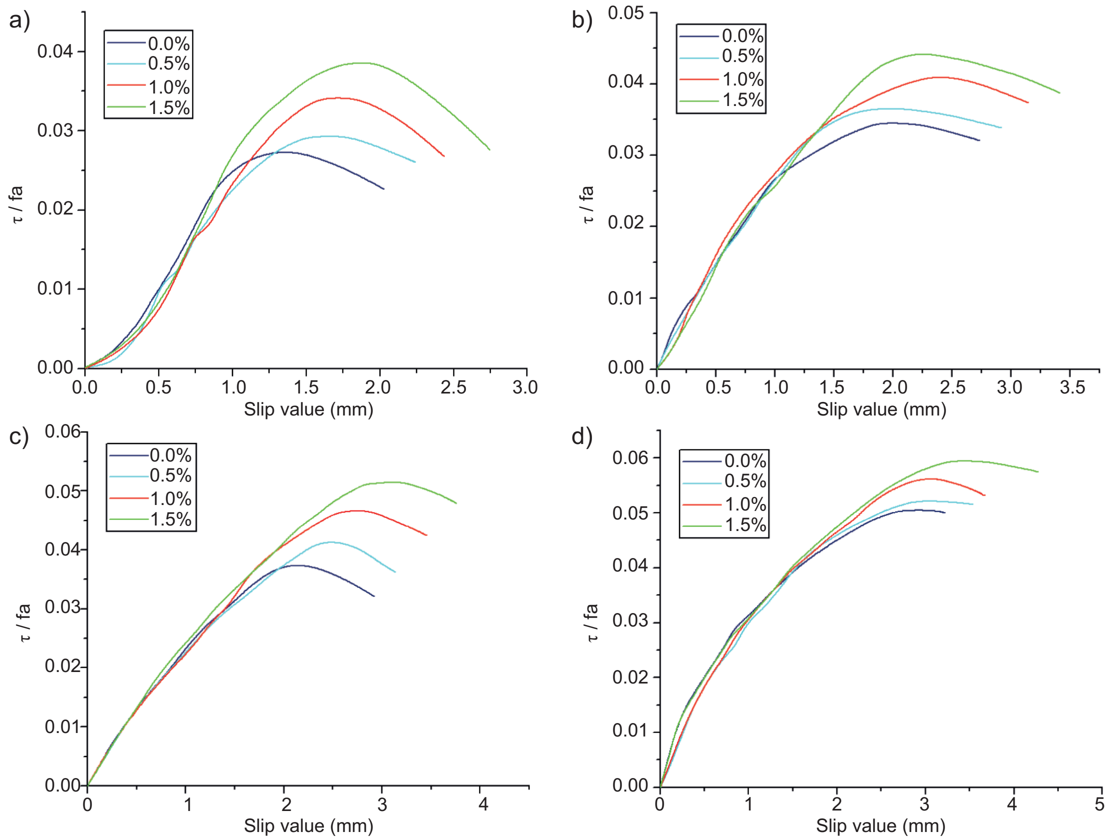

Fig. 7. Shear stress-slip curve under various shear stresses, a) Shear stress-slip curves when the compressive stress is 0.2 MPa; b) Shear stress-slip curves when the compressive stress is 0.6 MPa; c) Shear stress-slip curves when the compressive stress is 1.0 MPa; d) Shear stress-slip curves when the compressive stress is 1.4 MPa.

The derivation of formula of bonding compression-shear strength between industrial green fiber-reinforced concrete and old concrete

(1)Analysis of plastic limit of bonding-shear strength

For the concrete building structure, too low or too high estimation of the composite stress strength between old and new concrete will lead to the waste of building materials, and generally bury irreparable security risks in building design. Therefore, it is very necessary to deduce the bonding compression-shear strength formula of specimens under the composite stress state.

According to the failure phenomenon of the specimen, it is assumed that the failure mechanism of the bonding layer is as shown in **figure 8**, and the following assumptions are made:

a. Concrete 1 and concrete 2 represent new and old concrete respectively, and both of them are assumed to be ideal rigid plastic materials.
b. In the limit state, the specimen is composed of four parts: V_1, V_4 rigid body and V_2, V_3 plastic body.

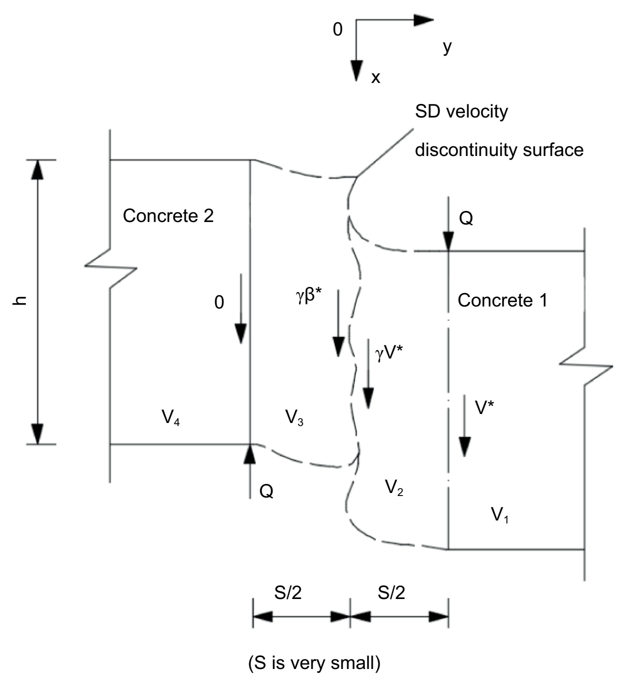

Fig. 8. Schematic diagram of failure mechanism.

c. SD represents the bonding layer with zero thickness, namely, the velocity discontinuity surface. r and β respectively represent a velocity reduction factor ($0 < r \leq 1$ and $0 < \beta \leq 1$).

Therefore, when the hydrostatic stress is small, the bonding-shear strength τ can be obtained from the upper bound theorem of limit analysis:

$$\tau = C\frac{1-\beta}{1+\beta} + \frac{\sigma_{S1}+\sigma_{S2}}{\sqrt{3}}\frac{\beta}{1+\beta} - tg\varphi\frac{1-\beta}{1+\beta}\sigma_n \tag{3.1}$$

Further transformed into:

$$\frac{2\tau}{f_{c1}+f_{c2}} = 2C\frac{1-\beta}{(1+\beta)(f_{c1}+f_{c2})} + \frac{2}{\sqrt{3}}\frac{\eta\beta}{1+\beta} - tg\varphi\frac{1-\beta}{1+\beta}\frac{2\sigma_n}{f_{c1}+f_{c2}} \tag{3.2}$$

In the type: $\eta = (\sigma_{S1} + \sigma_{S2})/(f_{c1} + f_{c2})$, σ_{S1} and σ_{S2} are the single tensile strength of concrete; C and φ are the comprehensive cohesive force and friction angle of the complex failure surface formed by the fracture between the interface agent and the old and new concrete. σ_n is the normal stress on the velocity discontinuity surface.

Since C, β, φ, σ_{S1}, and σ_{S2} in the above equations are unknown, they are difficult to apply. However, the factors affecting the bonding-shear strength of old and new concrete can be determined, that is, the reduction coefficient of interface bonding speed, the overall compressive strength of old and new concrete, etc. When the limit of β is 1, the velocity discontinuity surface expressed by SD will lose its meaning, that is, the bonding strength of the bonding transition layer is quite high. At this point, the failure mechanism is in a limit state, namely:

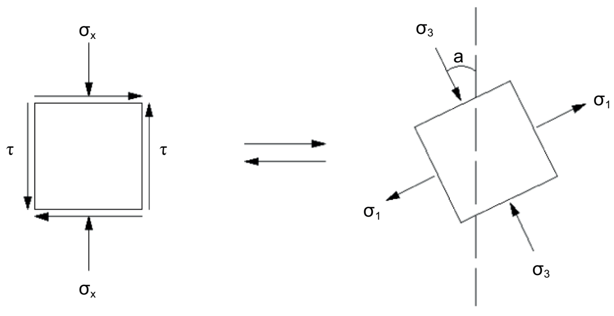

Fig. 9. Transition of stress state.

$$\tau = \frac{Q}{bh} = \frac{\sqrt{3}}{6}(\sigma_{S1}+\sigma_{S2}) \tag{3.3}$$

At this point, under the stress yield condition, the relation of (3.3) is expressed as the concrete structure is subjected to stress under the pure shear state, and its value is related to both the old and new concrete.

(2) The establishment of bonding compression-shear strength fitting formula of industrial green fiber reinforced concrete and old concrete

The compression-shear stress of concrete under the state of composite stress can usually be converted into the state of tension-compression composite stress in the main stress space, as shown in **figure 9**, and the expressions are shown in formula (3.4 and 3.5). At this point, the three-dimensional space coordinate system is taken as the reference, and the intermediate principal stress σ_2 is zero, so the principal compressive stress is changed to σ_3.

$$\sigma_1 = \frac{\sigma}{2} + \frac{1}{2}\sqrt{\sigma^2 + 4\tau^2} \tag{3.4}$$

$$\sigma_3 = \frac{\sigma}{2} - \frac{1}{2}\sqrt{\sigma^2 + 4\tau^2} \tag{3.5}$$

In the formula, σ is the normal stress and τ is the shear strength.

The strength criterion model proposed based on octahedral stress, American scholars Pister and Bresler used two forms of expression: Line and quadratic parabola (Bresler and Pister 1958). In general, due to the comparison of the two kinds of fitting forms under octahedral stress space, the estimated ultimate shear stress values of parabolic form fitting formula are more accurate than those of linear form fitting formula. Therefore, in order to consider the safety and reliability of the structure, the parabolic fitting formula under octahedral stress space was adopted for the bonding compression-shear strength formula under composite stress state in this test (Li 2017).

$$\frac{\tau_{oct}}{f_a} = \gamma_1 + \gamma_2\frac{\sigma_{oct}}{f_a} \tag{3.6}$$

$$\frac{\tau_{oct}}{f_a} = \gamma_{11} - \gamma_{12}\frac{\sigma_{oct}}{f_a} + \gamma_{13}\left(\frac{\delta_{oct}}{f_a}\right)^2 \tag{3.7}$$

Where, γ_1, γ_2; γ_{11}, γ_{12}, γ_{13} refer to two groups of undetermined coefficients, and τ_{oct} and σ_{oct} are stresses under octahedral space. Equation (3.7) is converted into the strength criterion under the principal stress space by referring to the following formulas (3.8) and (3.9).

$$\frac{\sigma_{oct}}{f_a} = \frac{1}{3}\sqrt{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2} \tag{3.8}$$

$$\sigma_{oct} = \frac{1}{3}(\sigma_1+\sigma_2+\sigma_3) \tag{3.9}$$

The converted strength criterion formula is as follows (3.10) :

$$\frac{\sqrt{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}}{3f_a} = \gamma_{11}-\gamma_{12}\frac{\sigma_1+\sigma_2+\sigma_3}{3f_a}+\gamma_{13}\left(\frac{\sigma_1+\sigma_2+\sigma_3}{3f_a}\right)^2 \tag{3.10}$$

Combined with formula (3.4) and (3.5), strength criteria of old and new concrete under plane compression-shear composite stress state can be obtained (Li 1997), as shown in (3.11) below.

$$\frac{\sqrt{2\sigma^2+6\tau^2}}{3f_a} = \gamma_{11}-\gamma_{12}\frac{\sigma}{3f_a}+\gamma_{13}(\frac{\sigma}{3f_a})^2 \tag{3.11}$$

$$\frac{\tau}{f_a} = \sqrt{\gamma_1'+\gamma_2'\frac{\sigma}{f_a}+\gamma_3'(\frac{\sigma}{f_a})^2+\gamma_4'(\frac{\sigma}{f_a})^3+\gamma_5'(\frac{\sigma}{f_a})^4} \tag{3.12}$$

In the formula $f_a = f_{c1} + f_{c1}) \times 0.067/2$; γ_1', γ_2', γ_3', γ_4', γ_5' are the coefficients related to the volume ratio ρ_f and length-diameter ratio l_f / d_f of recycled steel fibers.

In order to facilitate the calculation and take the variation of recycled steel fiber content into account, the octahedral stress fitting formula of ordinary old and new concrete specimens is taken as the reference. The above formula (3.12) is taken as the strength formula applicable to the unified compression-shear composite force of ordinary old and new concrete, industrial green fiber-reinforced concrete and old concrete.

The comparison results between the values calculated according to the above formula and the measured values in the test are shown in **table III**.

According to the data analysis, the ratios between the measured values in this test and the calculated values obtained according to the above calculation formula is between 0.88 and 1.13, indicating that the formula is effective.

FINITE ELEMENT NUMERICAL SIMULATION AND RESULTS ANALYSIS

Based on the analysis of the bonding failure performance between old and new concrete by the above compression-shear tests, the numerical simulation of the bonding compression-shear performance of the bonding interfaces between industrial green fiber-reinforced concrete and old concrete was carried out by using ABAQUS finite element numerical simulation and python computer language programming.

TABLE III. COMPARISON BETWEEN THE EXPERIMENTAL RESULTS AND THE CALCULATED RESULTS OF THE FORMULA FOR THE BONDING COMPRESSION-SHEAR STRENGTH BETWEEN OLD AND NEW CONCRETE.

No.	Content of recycled steel fibers / %	Average compression-shear strength of the test / MPa	Compressive stress / MPa	Strength of new concrete / MPa	The τ/f_a obtained from the test results	The τ/f_a obtained from the formula
1	0.0	0.656	0.2	40.34	0.027	0.024
2	0.5	0.691	0.2	40.34	0.028	0.025
3	1.0	0.831	0.2	40.34	0.034	0.037
4	1.5	0.938	0.2	40.34	0.038	0.043
5	0.0	0.829	0.6	40.34	0.034	0.031
6	0.5	0.891	0.6	40.34	0.037	0.040
7	1.0	0.998	0.6	40.34	0.041	0.045
8	1.5	1.086	0.6	40.34	0.045	0.048
9	0.0	1.037	1.0	40.34	0.042	0.038
10	0.5	1.094	1.0	40.34	0.045	0.043
11	1.0	1.202	1.0	40.34	0.049	0.044
12	1.5	1.281	1.0	40.34	0.052	0.056
13	0.0	1.220	1.4	40.34	0.050	0.046
14	0.5	1.259	1.4	40.34	0.052	0.057
15	1.0	1.368	1.4	40.34	0.056	0.059
16	1.5	1.461	1.4	40.34	0.060	0.065

TABLE IV. PARAMETERS OF EACH COMPONENT OF INDUSTRIAL STEEL FIBER-REINFORCED CONCRETE.

Component	Density (kg / m^3)	Tensile strength (MPa)	Modulus of elasticity (GPa)	Poisson's ratio	Fracture energy (N / m)
Concrete matrix	2400	1.8	33	0.16	110
Recycled steel fiber	7900	1800	216	0.3	—

Assignments of material properties

The material properties set in the numerical simulation are elastoplastic materials. According to the research results and tests of experts and scholars at home and abroad, the relevant parameters of industrial green fiber-reinforced concrete are selected as the following **table IV**.

The building of the model

The bonding surface between old and new concrete is a discontinuum, so the stress-strain relationship cannot be expressed by the elastic modulus. Therefore, in the three-dimensional ABAQUS finite element numerical simulation, the old and new concrete can be simulated by setting the bonding contact perpendicular to the normal direction of the bonding interface, the longitudinal tangential direction along the loading direction and parallel to the bonding interface, and the transverse tangential direction perpendicular to the loading direction and parallel to the bonding interface. The bonding compression-shear assembly model is shown in **figure 10**. During the simulation, the recycled steel fibers are generated by Python script and distributed evenly in the new concrete module as in the test (Ren and Li 2013).

The division of the grid

For the grid division of the model, a reasonable size of grid division can make the simulation results more accurate. Therefore, the size of grid division of concrete and recycled steel fibers in the finite element model is determined to be 10 mm in this paper according to the condition of the actual test and repeated simulation tests. The grid division of the model is shown in **figure 11**.

Stress nephograms of old and new concrete

This simulation discusses the numerical simulation of the bonding compression-shear performance between industrial green fiber-reinforced concrete and old concrete with the fiber volume ratio of 1.5% under the compressive stress of 0.8 MPa, 1.0 MPa and 1.4 MPa. Stress nephograms of concrete and recycled steel fibers are shown in **figure 12**, **figure 13** and **figure 14** below.

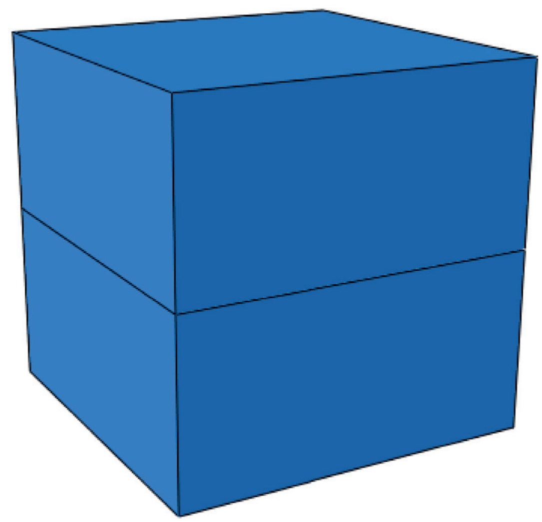

Fig. 10. The compression-shear model of old and new concrete.

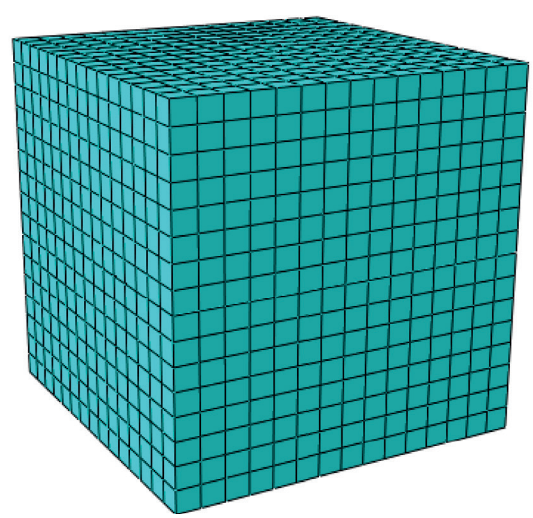

Fig. 11. The grid division of compression-shear simulation.

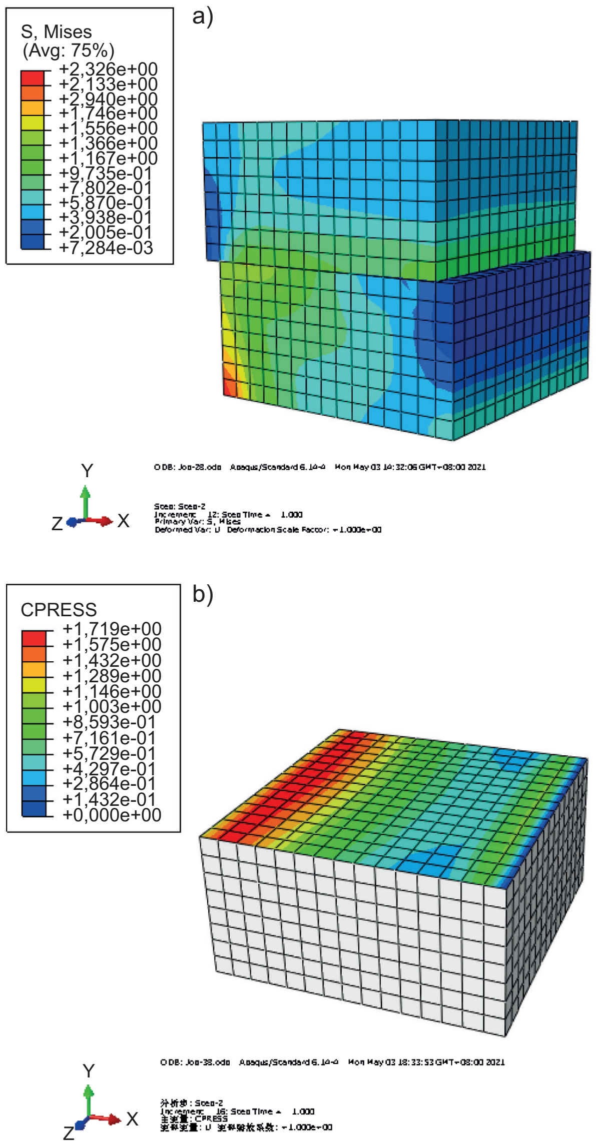

Fig. 12. Stress nephograms of test block under compressive stress of 0.8 MPa, a) The compression-shear model under compressive stress of 0.8 MPa; b) The compressive stress of the bonding surface under compressive stress of 0.8 MPa.

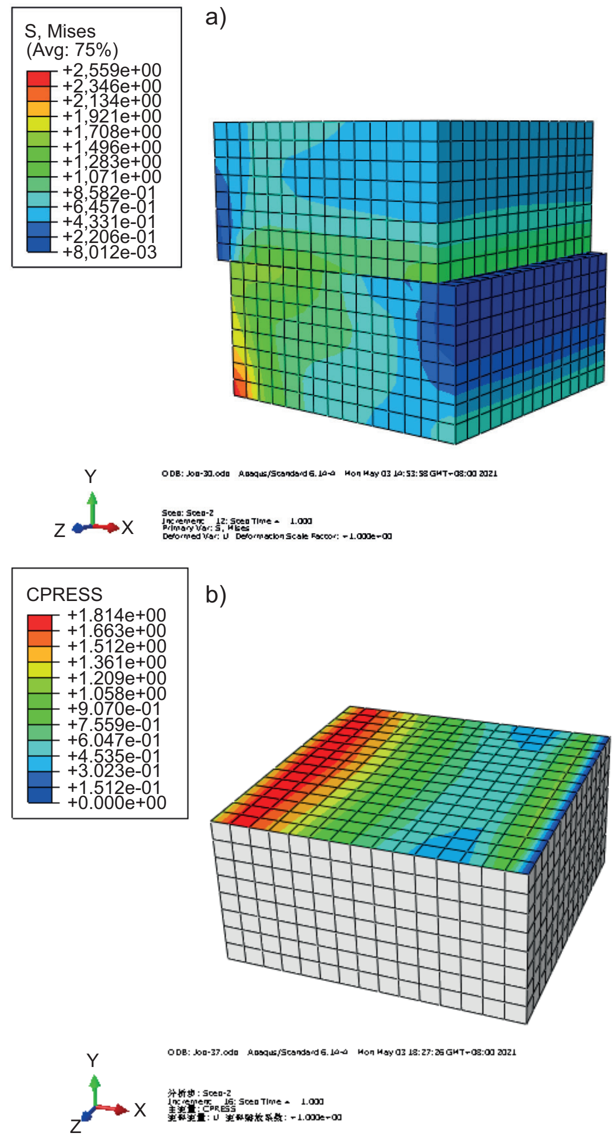

Fig. 13. Stress nephograms of test block under compressive stress of 1.0 MPa, a) The compression-shear model under compressive stress of 1.0 MPa; b) The compressive stress of the bonding surface under compressive stress of 1.0 MPa.

As can be seen from the figures above, as the compressive stress gradually increases, the shear stress borne by the bonded test block gradually increases, that is, the bonding compression-shear strength of specimens gradually increases with the increases of the compressive stress, which is consistent with the test situation. Under the case of three kinds compressive stresses, the stress at the left part of the bottom reinforcement end of the specimen is large, while the damage of both ends of the bottom of the test block is obvious during the test. It can be seen from the simulation that the shear stress on the bonding surface between old and new concrete is larger, especially the left part of the bonding surface. However, the damage on the right side was also evident during the test, but it was slightly better than the damage on the left. Therefore, it can be seen that the bonding surface between industrial green fiber-reinforced concrete and old concrete is the weak link of failure of specimens, which is

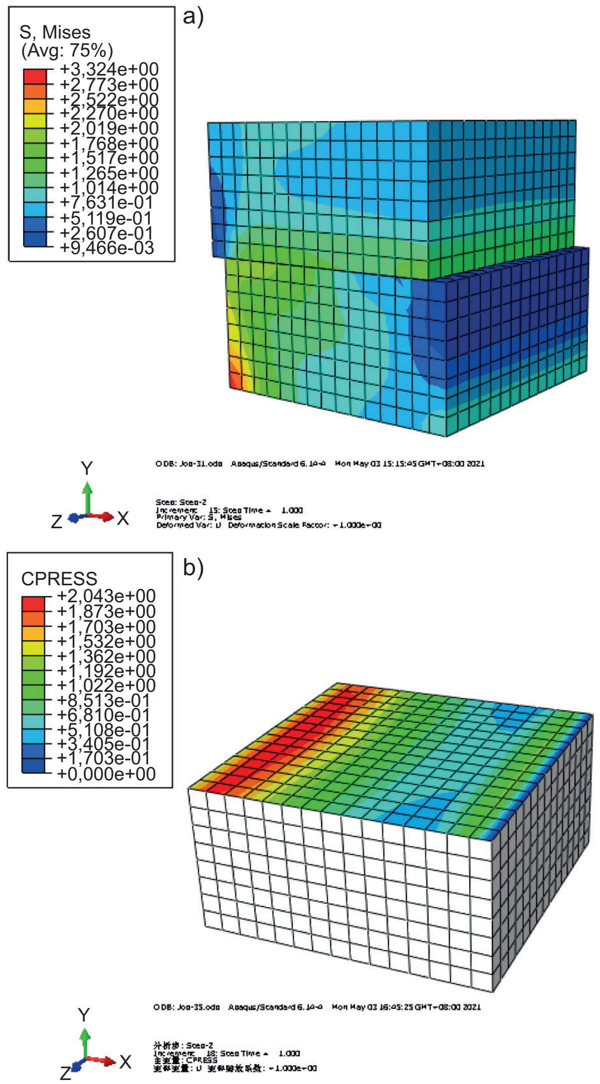

Fig. 14. Stress nephograms of test block under compressive stress of 1.4 MPa, a) The compression-shear model under compressive stress of 1.4 MPa; b) The compressive stress of the bonding surface under compressive stress of 1.4 MPa.

basically consistent with the phenomenon of bonding failure of old and new concrete in the actual test process. In addition, the old concrete test blocks are somewhat deformed when the compressive stress is 1.4 MPa in the simulation, which is also consistent with the situation that the old concrete test blocks appear more debris when the compressive stress is 1.4 MPa in the test.

Stress nephograms of recycled steel fibers

Figure 15 reflects the stress nephograms of steel fibers of specimens with the fiber volume ratio of 1.5% under different compressive stresses. As can be seen from figures, with the gradual increases of compressive stress, the shear stress of the recycled steel fibers gradually increases. The results show that adding a certain amount of recycled steel fibers into the new concrete can effectively improve the compression-shear performance of the industrial green fiber-reinforced concrete reinforced old concrete under the composite stress state. It also indicates that with the increases of compressive stress, the bonding compression-shear strength of specimens gradually increases, which are basically consistent with the test situation. At the same time, it can be seen from figures that the steel fibers near the bonding surfaces between the old and new concrete are subjected to the large shear stress, which is also basically in line with the actual situation.

Comparison of shear stress-slip curves

The comparison of shear stress-slip curves of specimens obtained from the test and numerical simulation are shown in the figures below.

It can be seen from **figure 16** that the shear stress-slip curves of finite element numerical simulation are relatively consistent with the shear stress-slip curves obtained in the test process (Chen and Zheng 2014), and the shear stress values obtained by simulation are slightly larger than those obtained in experiment. When the interface reaches the peak shear stress, the sliding process of the old and new concrete interface pushes the steel fibers leaking out of interface to bear further shear stress, which increases the mechanical biting force of the interface between the old and new concrete. Therefore, the bearing capacity of specimens decreases slowly after reaching the peak shear stress. Because the bonding compression-shear process between industrial green fiber-reinforced concrete and old concrete is a complex stress process, the numerical simulation can not fully reflect the influence of all factors on the interface bonding (Chen 2016). However, after considering the influence of steel fiber content and different compressive stresses, it can still approximately reflect the working condition of the interface between old and new concrete under the composite compression-shear stress state, so it can be further used as an auxiliary analysis.

Through the above simulation analysis, it can be clearly known that the stress distribution and variation trend are generally similar when the interfaces between old and new concrete are debonded and damaged under different compressive stresses, and the maximum stress load mainly appears in the bonding area and the boundary constraint area of the specimen, which are basically similar to the results obtained in the test process.

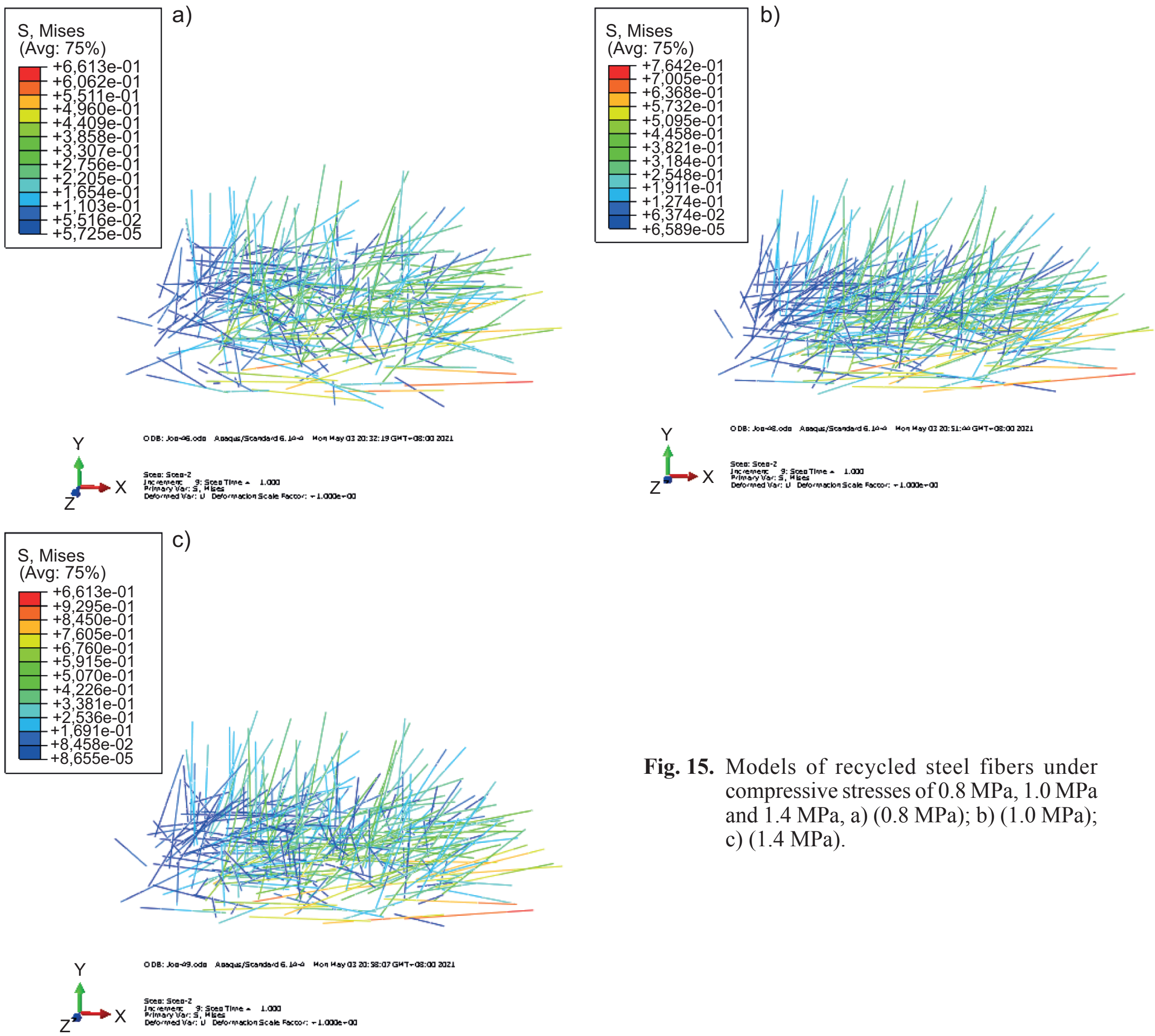

Fig. 15. Models of recycled steel fibers under compressive stresses of 0.8 MPa, 1.0 MPa and 1.4 MPa, a) (0.8 MPa); b) (1.0 MPa); c) (1.4 MPa).

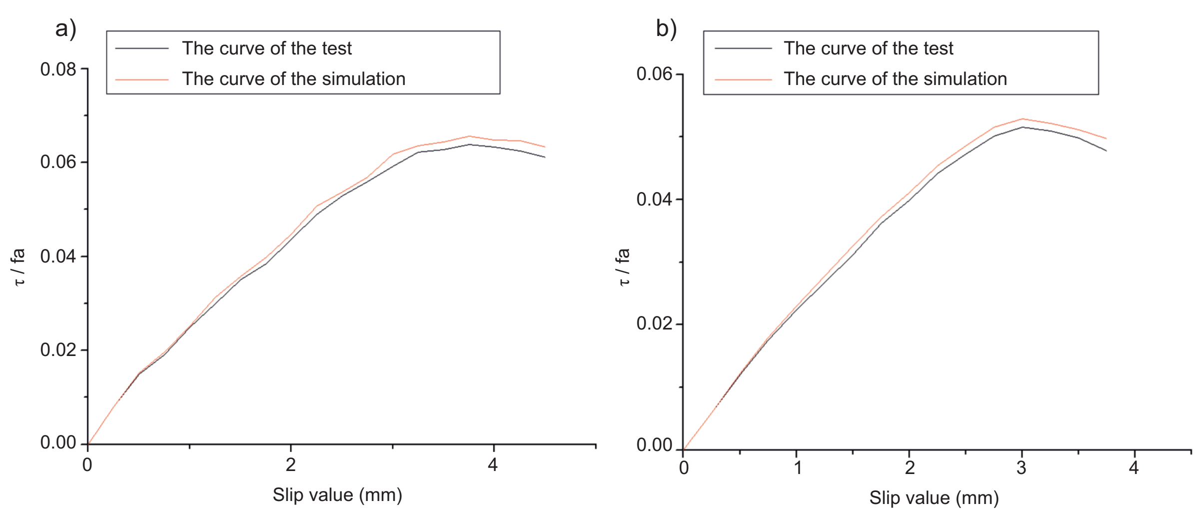

Fig. 16. Comparison of shear stress-slip curves of the test and simulation, a) Shear stress-slip curves when compressive stress is 1.0 MPa; b) Shear stress-slip curves when compressive stress is 1.4 MPa.

CONCLUSIONS AND PROSPECTS

Conclusions

In this paper, with the same interface roughness, the influence of different compressive stresses, types of steel fibers and volume ratios of recycled steel fibers on the bonding compression-shear performance of steel fiber-reinforced old and new concrete specimens under the composite stress state was investigated with the help of a new self-made fixture, and combining with ABAQUS finite element numerical simulation, the solid models of industrial green fiber-reinforced concrete were established. After comparing and analyzing the test results, the conclusions are as follows:

(1) When the volume ratio of steel fibers is the same, the bonding compression-shear performance of specimens gradually increases with the increases of compressive stress acting perpendicular to the shearing surface within the range of low compressive stress in this test. When the compressive stress is from 0.2 MPa to 1.0 MPa, the increased amplitude of the bonding compression-shear performance of specimens gradually increases, and when the compressive stress is from 0.6 MPa to 1.0 MPa, the increased amplitude of the bonding compression-shear performance of specimens reaches the maximum. When the compressive stress is from 1.0 MPa to 1.4 MPa, the increased amplitude of the bonding compression-shear performance of specimens decreases.

(2) When the volume ratio of steel fibers is the same, the effect of improving the bonding compression-shear performance between old and new concrete with recycled steel fibers is better than normal steel fibers under the same compressive stress. Therefore, when studying the basic mechanical properties between old and new concrete in the future, the full and reasonable use of recycled steel fibers can not only save resources and protect the environment, but also provide a new research direction for the green and sustainable development of building structures.

(3) When the compressive stress is the same, the bonding compression-shear performance between old and new concrete gradually increases with the increases of the volume ratio of steel fibers. When the fiber content is from 0.0% to 1.0%, the increased amplitude of the bonding compression-shear performance of specimens gradually increases, and when the fiber content is from 0.5% to 1.0%, the increased amplitude of the bonding compression-shear performance of specimens reaches the maximum. When the fiber content is from 1.0% to 1.5%, the increased amplitude of bonding compression-shear performance of specimens decreases. Therefore, in the future research, the recycled steel fibers with volume ratio of 1.5% can be added into the concrete to improve the bonding compression-shear performance of specimens, which also provides references for the recycling of wire from waste tires.

(4) On the basis of the test, the bonding compression-shear performance of industrial green fiber-reinforced concrete and old concrete with the fiber content of 1.5% under different compressive stresses was simulated, and the simulation results are basically in agreement with the test results. However, the failure phenomenon of specimens in the simulation is somewhat different from that in the test. Because the finite element numerical simulation does not consider the cases as well as the test, the error is basically within the allowable range.

Prospects

In this paper, the bonding compression-shear performance between normal steel fiber-reinforced old and new concrete, industrial green fiber-reinforced concrete and old concrete under the basic composite stress state was studied. However, due to the lack of research and some subjective and objective reasons, there are still some problems worth exploring in the future. The details are as follows:

(1) In the bonding compression-shear tests, the maximum compressive stress is only 1.4 MPa, and the maximum content of recycled steel fibers is only 1.5%. The influence of higher compressive stress and fiber volume ratio on the bonding compression-shear performance of specimens was not reflected, which needs to be further studied and discussed.

(2) In the process of test, it is found that the appearance of recycled steel fibers at the bonding surface has a certain influence on the bonding performance of the interface. However, in the process of concrete pouring, the fibers were mixed into the new concrete specimens in random distribution. Therefore, considering the influence of a better distribution mode of steel fibers in the new concrete on the bonding performance of the interface between the old and new concrete is also a topic that worth studying in the future.

DATA AVAILABILITY

The data supporting the findings of this study are included within the article.

CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

AUTHORS CONTRIBUTIONS

Theoretical analysis: Yan LI, Rong-Hua ZHAO. Numerical simulation: Wen-Yang DONG, Rong-Hua ZHAO. Experimental: Rong-Hua ZHAO, Qi-Ren JIANG. Experimental analysis: Rong-Hua ZHAO, Qi-Ren JIANG.

ACKNOWLEDGMENT

This work was supported in part by the National Key Research and Development Program of China (No.2017YFC0806100) and the Jilin Scientific and Technological Planning Project (No.20200403161SF).

REFERENCES

Liu Ch.Q. (2014). Experimental study of old and new concrete interface mechanism of paste. Master's thesis. Chang'an University. Xi'an, Shanxi Province, China, 73pp.

Cui H. (2018). Study on influencing factors and mechanism of bonding between old and new concrete under the action of new interfacial agents. Master's thesis. North China University of Water Resources and Electric Power. Zhengzhou, Henan Province, China, 77pp.

Chen F. and Zheng J.L. (2005). Research development and application prospect of bonding between old and new concrete. Journal of Fuzhou University (Natural Science Edition) (S1), 162-165. https://doi.org/10.3969/j.issn.1000-2243.2005.z1.032

Cheng H.Q., Liu G.L. and Gao D.Y. (2013). Experimental study on bonding shear performance of steel fiber-reinforced concrete to old concrete. Journal of Hydroelectric Engineering 32(04), 177-181+192. https://doi.org/CNKI:SUN:SFXB.0.2013-04-031

Peng G.F., Niu X.J. and Long Q.Q. (2015). Experimental study of strengthening and toughening for recycled steel fiber reinforced ultra-High performance concrete. Key Engineering Materials 629-630, 104-111. https://doi.org/10.4028/www.scientific.net/KEM.629-630.104

Kang Z.Z. and Zhang B.J. (2011). Scrap tires recycling in landscape engineering. Advanced Materials Research 374-377, 1571-1575. https://doi.org/10.4028/www.scientific.net/AMR.374-377.1571

Carrillo J., Marriaga J.L. and Baez F. (2020). Properties of steel fiber reinforced concrete using either industrial or recycled fibers from waste tires. Fibers and Polymers 21(9), 2055-2067. https://doi.org/10.1007/s12221-020-1076-1

Chen P.W., Fu X. and Chung D. (1995). Improving the bonding between old and new concrete by adding carbon fibers to the new concrete. Cement & Concrete Research 25(3), 491-496. https://doi.org/10.1016/0008-8846(95)00037-D

Caggiano A., Folino P., Lima C., Martinelli E. and Pepe M. (2017). On the mechanical response of hybrid fiber reinforced concrete with recycled and industrial steel fibers. Construction and Building Materials 147, 286-295. https://doi.org/10.1016/j.conbuildmat.2017.04.160

Bing L.A.B., Jz B., Xw B., Jg B., Zdb C. and Xu H.B.C. (2021). Mechanical performance and failure criterion of coral concrete under combined compression-shear stresses. Construction and Building Materials 288, 123050. https://doi.org/10.1016/j.conbuildmat.2021.123050

Simalti A. and Singh A.P. (2021). Comparative study on performance of manufactured steel fiber and shredded tire recycled steel fiber reinforced self-consolidating concrete. Construction and Building Materials 266(2017), 121102. https://doi.org/10.1016/j.conbuildmat.2020.121102

Cheng H.Q. (2007). Experimental study on bonding properties of fiber-reinforced concrete to old concrete. Doctoral thesis. Zhengzhou University. Zhengzhou, Henan Province, China, 177pp.

Liu K.H. (2014). Experimental study on properties of recycled concrete under combined compressive and shearing stresses. Master's thesis. Harbin Institute of Technology. Harbin, Heilongjiang Province, China, 80pp.

Yuan Q. and Liu J. (2001). Study on bonding shear strength of old and new concrete. Journal of Building Structures (02), 46-50. https://doi.org/10.3321/j.issn:1000-6869.2001.02.008

Zhao Zh.F., Zhao G.F. and Huang Ch.K. (1999). Research on the tension-shear properties of the adhesion of new and old concrete. Journal of Building Structures (06), 26-31. https://doi.org/10.14006/j.jzjgxb.1999.06.004

Nourmohammadi N., O'Dowd N.P. and Weaver P.M. (2020). Effective bending modulus of thin ply fibre composites with uniform fibre spacing. International Journal of Solids and Structures 196-197, 26-40. https://doi.org/10.1016/j.ijsolstr.2020.04.004

Liu S.G., Bai R., Yan C.W. and Deng Y.H. (2018). Experimental study and theoretical calculation of bending stiffness of reinforced fiber reinforced cement matrix composite beams. Journal of Building Structures 39(S2), 176-182. https://doi.org/10.14006/j.jzjgxb.2018.S2.024

Raju R.A., Lim S., Akiyama M. and Kageyama T. (2020). Effects of concrete flow on the distribution and orientation of fibers and flexural behavior of steel fiber-reinforced self-compacting concrete beams. Construction and Building Materials 262, 119963. https://doi.org/10.1016/j.conbuildmat.2020.119963

Diab A.M., Elmoaty A.M.A.E. and Eldin M. (2017). Slant shear bond strength between self compacting concrete and old concrete. Construction and Building Materials 130(jan.15), 73-82. https://doi.org/10.1016/j.conbuildmat.2016.11.023

Tschegg E.K., Ingruber M., Surberg C.H. and Monger F. (2000). Factors influencing fracture behavior of old-new concrete bonds. American Concrete Institute Materials Journal 97(4), 447-453. https://doi.org/10.1016/S0040-6090(00)00907-X

Liu J. (2000). Study on the mechanics performance of adherence of new on old concrete. Doctoral thesis. Dalian University of Technology. Dalian, Liaoning Province, China, 126pp.

Li Y., Wang X.P., He Zh.G. and Fang Q. (2020). Experimental study on shear performance of industrial waste fiber reinforced cement matrix composites. Industrial Building 50(12), 88-92+159. https://doi.org/10.13204/j.gyjzG19100806

Bresler B. and Pister K.S. (1958). Strength of concrete under combined stresses. Journal Proceedings. 1958, 55(9): 321-345.

Li J. (2017). Experimental Study on behavior of recycled concrete under combined compressive and shearing stresses. Master's thesis. Guangxi University. Nanning, Guangxi Province, China, 70pp.

Li J.K. (1997). Experimental research on behavior of high-strength concrete under combined compressive and shearing stresses. Journal of Civil Engineering (03), 74-80. https://doi.org/CNKI:SUN:TMGC.0.1997-03-010

Ren X. and Li J. (2013). Multi-scale based fracture and damage analysis of steel fiber reinforced concrete. Engineering Failure Analysis 35, 253-261. https://doi.org/10.1016/j.engfailanal.2013.01.029

Chen F. and Zheng J.L. (2014). Finite element analysis of bonding-slip relationship between old concrete and freshly cured self-compacting concrete. Journal of Wuhan University (Engineering Science) 47(6), 774-778. https://doi.org/CNKI:SUN:WSDD.0.2014-06-011

Chen Y.L. (2016). The numerical analysis on interfacial bonding performance between steel fiber polymer concrete and old concrete. Master's thesis. Chongqing Jiaotong University. Chongqing, China, 93pp.